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Transplanting Tree Ferns to Promote Their Conservation in Mexico

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Abstract.—Adult tree ferns of the genera *Cyathea* and *Alsophila* are frequently harvested from tropical forest remnants near the city of Cuetzalan (Puebla, Mexico). Local artisans use the adventitious roots that surround tree fern stems as substrate to make handicrafts. In this region, tree ferns regenerate abundantly in disturbed areas such as roadsides, in which they suffer high mortality due to weeding and other road maintenance activities. Transplantation of young tree ferns from these areas to safe sites could contribute to the *ex situ* conservation of the species. The sale of transplanted tree ferns could also provide local families with an additional source of income. We identified and estimated the abundance of all tree fern species that occurred along roadsides in this region. We evaluated the viability of transplanting young tree ferns of *Cyathea divergens* and *Alsophila firma* to different conditions of light availability. While only 30% of the individuals naturally growing along roadsides survived for 1 year, *C. divergens* transplants experienced 73.3 and 86.7% survival and *A. firma* transplants experienced 93.3 and 40% survival when planted in safe sites under open canopy and in 50% shade, respectively. Transplants of *C. divergens* produced more fronds and grew faster in height than transplants of *A. firma*. Individuals of both species transplanted to 50% shade produced more fronds and grew faster than conspecifics transplanted to open canopy areas. Transplantation proved to be a low time- and cost-demanding strategy to promote conservation of native tree fern populations while providing local people with a potentially profitable alternative to replace handicraft production.

Key Words.—*Cyathea*, *Alsophila firma*, management, Mexico, transplantation, tree fern, tropical montane forest

Disregarding law prohibitions, artisans in the region of Cuetzalan, Mexico harvest the stems of adult tree ferns of at least two species, *Cyathea divergens* var. *tuerckheimii* R.M. Tryon, and *C. fulva* M. Martens et Galeotti, to produce handicrafts (Eleutério and Pérez-Salicrup, 2006). Both species are listed in the Mexican law as threatened by land-use and land-cover changes (SEMARNAT, 2000).

Adult tree ferns are mostly harvested from natural populations that occur in remnants of tropical montane forests. These forests are among the most

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endangered ecosystems in Mexico (Diario Oficial de la Federación, 2001; Luna *et al.*, 2001). As a result, harvest contributes to increased mortality rates and jeopardizes the future regeneration of native tree ferns in forests that are already vulnerable (Eleutério and Pérez-Salicrup, 2006).

Although tree fern species are often restricted to shaded and high moisture sites, at least three *Cyathea* and one *Alsophila* species commonly establish and grow in ruderal habitats, such as roadsides, near Cuetzalan (pers. obs.). Therefore, any management policy aiming to preserve tree fern species in this region must consider their occurrence in different habitats (Werth and Cousens, 1990), from forest remnants to disturbed areas. However, no study has yet documented the establishment requirements of tree fern species in this region. Moreover, few studies have looked at management requirements for conserving the 13 *Cyathea* spp. that are currently considered endangered by the Mexican law (Diario Oficial de la Federación, 2001; Bernabe *et al.*, 1999).

Our study focused on providing basic information to allow the *ex situ* conservation of endangered species of the family Cyatheaceae. Tree ferns are usually propagated *ex situ* through spores, vegetative tissues (e.g., Finnie and Staden, 1987; Suzuki *et al.* 2005), and occasionally, by planting fronds (e.g., *Cibotium splendens* (Gaudich.) Krajina ex Skottsb.; Hensley, 1997) or the apical meristems of harvested adults (e.g., *Dicksonia antarctica* Labill.; Forestry Commission, 2001). Although not evaluated for the tree fern species that occur in the region of Cuetzalan, transplantation of seedlings and young plants is commonly performed to promote *ex situ* conservation and *in situ* enrichment planting of endangered species (Primack, 2002). Transplants are more likely to successfully establish and grow when environmental conditions of the sites where they naturally occur are similar to the ones of the areas they are relocated to (Jones and Hayes, 1999; Montalvo and Ellstrand, 2001).

For the species of Cyatheaceae native to the region of Cuetzalan, transplantation from roadsides to safe sites could be an important strategy for *ex situ* conservation. Along these roadsides, young tree fern sporophytes (≤ 50 cm tall) normally experience high mortality rates due to annual cutting of herbaceous vegetation for road maintenance (pers. obs.). A bank of sporophytes could be created by transplanting them from exposed to protected areas under adequate environmental conditions. If tree fern transplantation proves successful, cost and time associated with spore or gametophyte germination could be avoided. The sale of young tree ferns for horticultural purposes could potentially substitute for income obtained by selling handicrafts fashioned from tree fern adventitious roots, and consequently contribute to their *in situ* conservation.

To evaluate the feasibility of using transplants of *Cyathea* and *Alsophila* spp., extracted from roadsides for *ex situ* conservation, we first documented the tree fern species that naturally established along the margins of a major road used to access the city of Cuetzalan. We then transplanted young tree ferns to sites subjected to different light conditions to compare their survival and growth rates among species and treatments. Based on these data, we provide basic guidelines for tree fern conservation in the study region.

TABLE 1. Maximum stem height (m) of adults and altitudinal ranges (meters above sea level) in which the studied species of tree ferns typically grow.

Species	Adult maximum stem height (m)	Habitat Altitudinal Range (m.a.s.l.)
Cyathea divergens var. *tuerckheimii*	12	450–2400
Cyathea fulva	12	800–2700
Alsophila firma	10.5	750–2000
Cyathea costaricensis	8	250–750

METHODS

Study site.—This study was conducted in the vicinities of the city of Cuetzalan (20° 01′ 33″ N–97° 31′ 37″ W), in the northern region of the state of Puebla, central-eastern Mexico. Study areas were located at elevations ranging from 500 to 1470 meters above sea level (m.a.s.l.). Annual precipitation averages 4141 mm, with all months receiving > 100 mm of rainfall. Mean annual temperature is 19.4°C, ranging from 14.3°C in January, to 22.9°C in June (Instituto Mexicano de Tecnología del Água, 2000). The landscape is dominated by shade coffee plantations with diversified overstory tree canopies, and tropical montane forest remnants.

Study species.—Three species of the genus *Cyathea* and one species of the genus *Alsophila* were found along roadsides in a 670–1420 m altitudinal range: *C. divergens* var. *tuerckheimii*, *C. fulva*, *C. costaricencis* (Mett. ex Kuhn) Domin. (Mickel and Beitel, 1988), and *Alsophila firma* (Baker) D.S. Conant (Mickel and Smith, 2004). All species are protected by Mexican law (Diario Oficial de la Federación, 2001).

Cyathea spp. typically have trunks that range from approximately 10 cm diameter at breast height (DBH) to approximately 130 cm with the mantle of adventitious roots. Stems and stipes are scaly, and stipes may present spines (Mickel and Beitel, 1998). Adult stems are occasionally bent due to mechanical damage and to the posterior recovery of vertical growth (Seiler, 1981). Adults of both *C. divergens* var. *tuerckheimii* and *C. fulva* may present 12 m tall stems and grow in sites between 450–2400 and 800–2700 m.a.s.l., respectively. *Cyathea costaricencis* may grow to 8 m tall in relatively drier environments usually located between 250 and 750 m.a.s.l. (Table 1; Mickel and Beitel, 1998).

Species of the genus *Alsophila* also present scaled stems and stipes, but petiole scales have characteristic apical setae (Korall *et al.* 2007). Most species grow between 1000 and 2000 m.a.s.l. of elevation, rarely occurring at altitudes below 250 m.a.s.l. Adults of *A. firma* grow up to 10.5 m tall, and are typically encountered between 750 and 2000 m.a.s.l. (Table 1). Stems may branch by adventitious buds (Mickel and Smith, 2004; Tryon and Tryon, 1982).

Abundance of tree ferns along roadsides.—We counted, identified and measured the height of all tree ferns taller than 0.5 m growing within distances ≤ 2 m from the pavement along 16 km of the main highway to access the city of

Cuetzalan. This highway connects the region to the state's capital city, Puebla. We assigned each identified tree fern to the following five height categories: 0.5–1.0, 1.1–2.0, 2.1–3.0, 3.1–4.0, and > 4.0 m. In addition, we divided the tree ferns encountered along the roadsides into three altitudinal ranges: 670–920 m.a.s.l., 921–1170 m.a.s.l., and 1171–1420 m.a.s.l. We only sampled tree ferns above 0.5 m in height because we were interested in quantifying the abundance of individuals that had successfully established along roadsides.

Experimental transplants.—In October 2003, we collected tree ferns of the two species that presented a high number of individuals with a stem height between 10 and 50 cm, encountered within a 700–950 m.a.s.l. altitudinal range. Thirty *C. divergens* and 30 *A. firma* plants ranging 17–50 cm tall were excavated with spades from roadsides. Tree ferns were extracted with their entire root systems and approximately 1000 cm^3 of local soil. Plants within this altitudinal range were selected to minimize environmental heterogeneity between the site they were extracted from and the ones they were transplanted to, which were located at 700 m.a.s.l.

Fifteen transplants of each species were planted into a 50% shade greenhouse, and fifteen were planted in an open (full sun exposure) garden. Plants were transplanted within two hours into holes 20–30 cm diameter and 30 cm depth. Holes were filled with local soil mixed with organic compost. We cut all fronds with fully expanded pinnae to minimize transpiration. We marked all fiddleheads (i.e., emerging leaves) at the beginning of the experiment and in subsequent censuses. To evaluate growth rates we measured stem height (to the nearest 0.5 mm), from the base of the newest crosier to the soil surface, monitored frond production every 2.5 months for 1 yr (from October 2003 to November 2004), and reported mean values ± SE for the study period. Fronds with ≥ 10% green tissue were considered alive (*sensu* Durand and Goldstein, 2001).

To investigate the mortality of tree ferns along roadsides, in March 2003 we randomly selected 60 tree ferns < 30 cm tall of each *C. divergens* and *C. fulva*, the two species that presented a higher number of individuals in this size category, growing in altitudes ranging from 900 and 1200 m.a.s.l. This altitudinal range was selected to include the extension of roadsides that would be weeded during the period we performed our study. To verify the effect of the transplantation procedure, we used a spade to extract half of the plants of each species with their entire root systems. We subsequently replanted each plant into the same spot they had been extracted from (henceforth called transplanted control individuals). We measured stem heights before transplanting, and cut all mature fronds with fully expanded pinnae to reduce water loss. We monitored plant survival for both transplanted control individuals and non-transplanted individuals, every 3 mo from March 2003–April 2004.

We used failure time analyses to compare survival rates between species and between treatments in both experiments (Fox, 2001). We performed Cox proportional hazard model and log-rank tests (Pyke and Thompson, 1986) with SPlus 6.0 (Insightful Corp. Seattle, USA). We used linear and quadratic regressions between the initial and final stem heights to determine the model

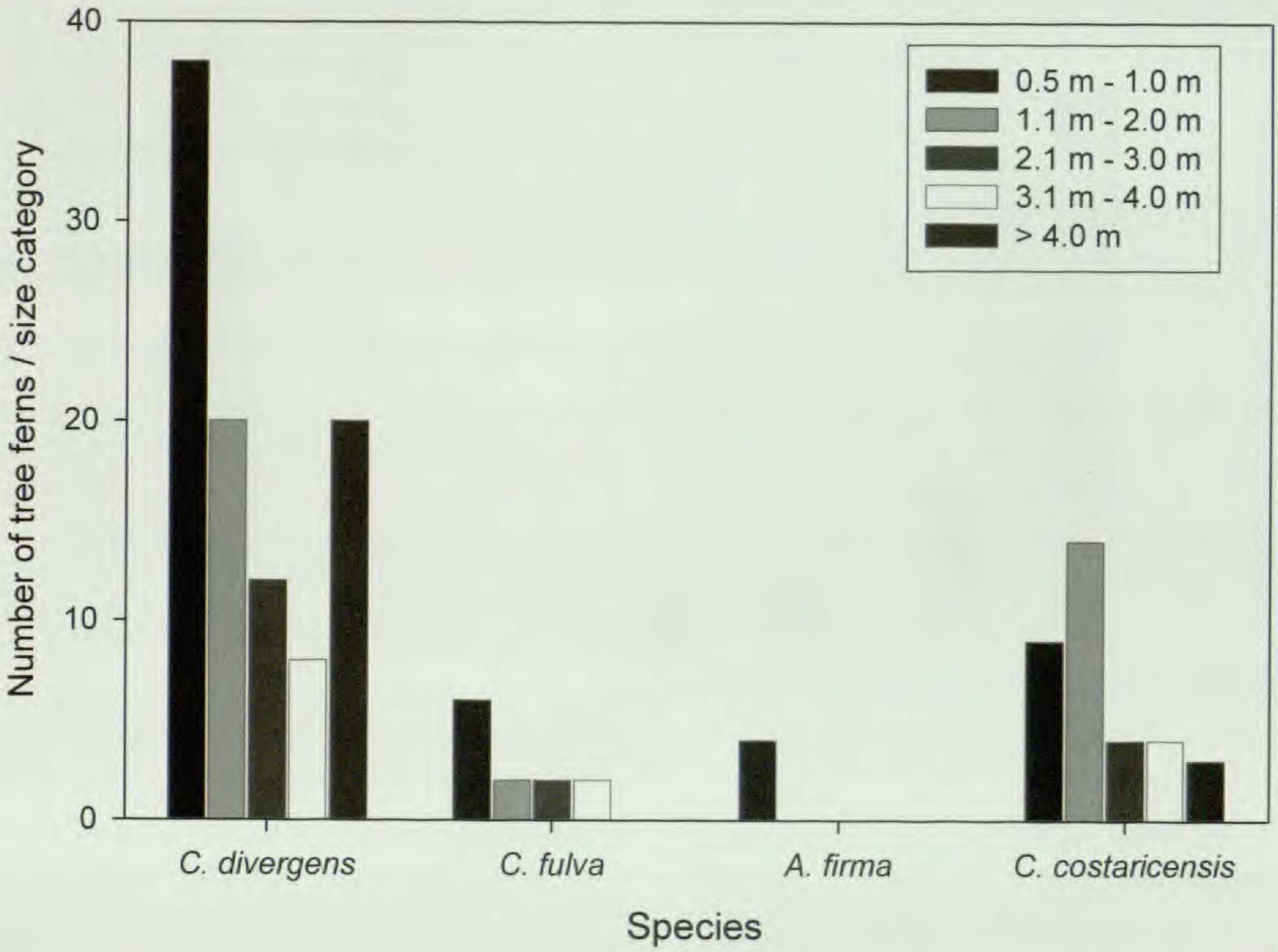

FIG. 1. Number of tree ferns in several size categories found for the three species of *Cyathea* and one species of *Alsophila* encountered along the roadside near the city of Cuetzalan del Progreso.

that best fit the patterns of stem growth (Sokal and Rohlf, 1995). Initial and final stem heights were linearly related, and therefore we performed a Pearson correlation analysis to evaluate the relationship between initial stems height and total number of fronds produced. We compared growth and frond production between species and treatments using a two way ANOVA without replication.

RESULTS

Abundance of tree ferns along roadsides.—Cyathea divergens and *C. costaricensis* were the most abundant tree fern species sampled along roadsides, with 96 and 34 individuals, respectively. Both species were represented in all height categories (Fig. 1). Only twelve plants of *C. fulva* and four of *A. firma* > 50 cm were encountered within the sampled area. Few plants taller than 3 m of both species were recorded (Fig. 1). *Cyathea divergens* was abundant along the whole altitudinal range sampled, while all the 34 plants of *C. costaricensis* were sampled within altitudes between 670 and 920 m (Fig. 2). Less than 10 individuals of *C. fulva* and *A. firma* were sampled in the whole study area. *A. firma* was restricted to altitudes between 921–1170 m, while *C. fulva* was only recorded in the other two altitudinal ranges.

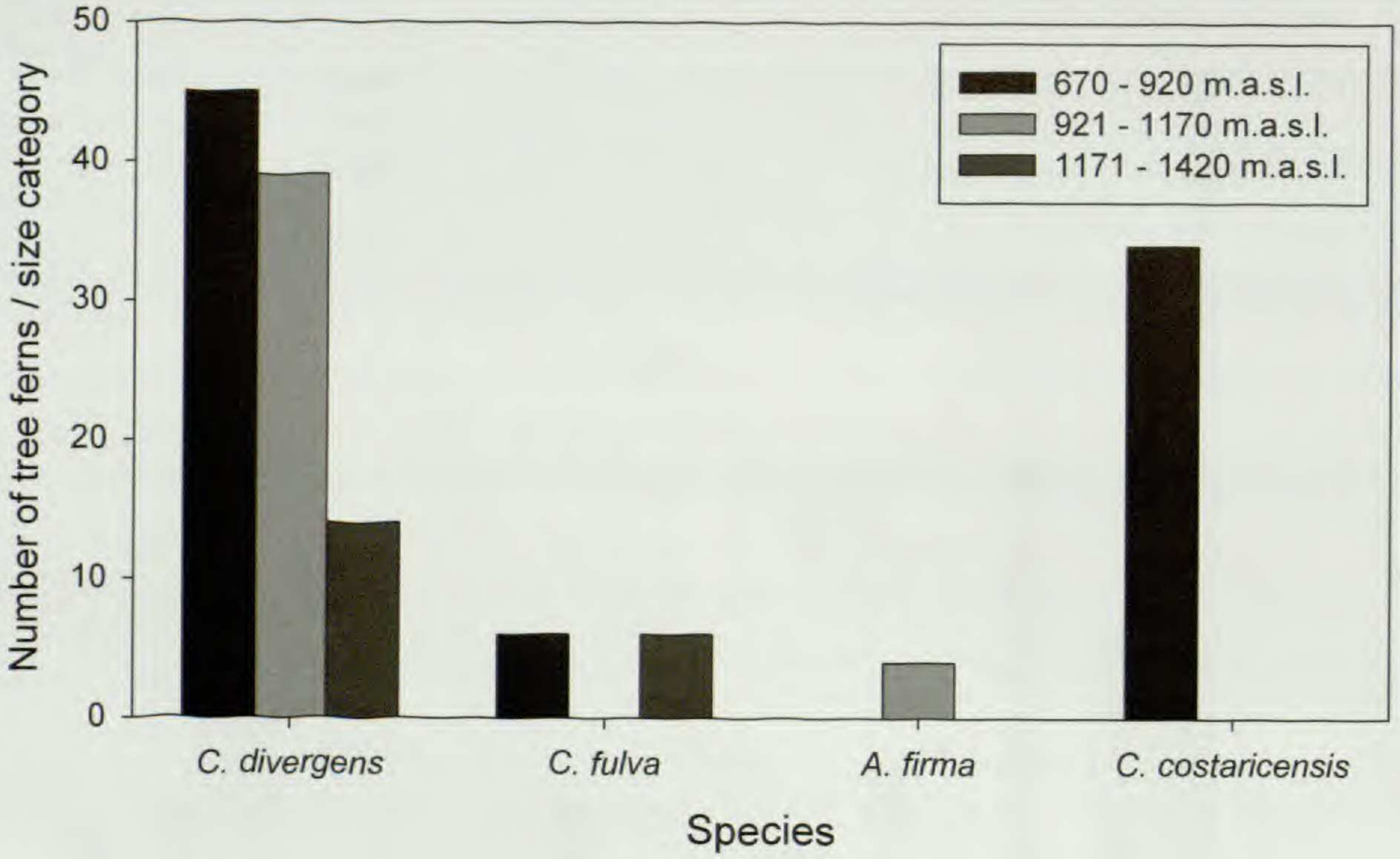

FIG. 2. Number of tree ferns of the four studied species by altitudinal range growing along the roadside.

Survival analyses.—While *C. divergens* experienced 73.3 and 86.7% survival, *A. firma* experienced 93.3 and 40% survival after 1 yr in open canopy and 50% shade, respectively. Survival curves did not differ between species (Fig. 3; log rank, $\chi^2 = 1.2$, df = 1, $P > 0.25$) or light treatments (Fig. 3; log rank, $\chi^2 = 3.2$, df = 1, $P > 0.05$). Survival rates were not affected by the initial height of stems ($z = -1.18$, $P > 0.2$), species ($z = 1.58$, $P > 0.10$), or light treatment ($z = -1.81$, $P > 0.05$) (likelihood ratio test = 6.58, df = 3, $P > 0.05$). Tree ferns of *C. divergens* transplanted to safe sites, whether open or shaded areas, survived more than those left on roadsides (control and transplant control; see Figs. 3 and 4). Less than 50% of the transplants of both *C. divergens* and *C. fulva* survived for more than 6 mo when left along the roadsides. After 1 yr from the beginning of the experiment, approximately 37% of the control individuals of *C. fulva* survived, while less than 10% of *C. divergens*, or of the plants assigned to the other treatments, survived (Fig. 4). In general, plants kept as controls had greater survival than the controls for the transplantation method.

Growth analyses.—Stem growth in height was between 4–5 mm/mo either in the sun or shade treatments and for both studied species in the first months after transplantation. Frond production was lower in the first three months than subsequent months (approximately 0.6 fronds/mo, in comparison to the 1.0–1.2 fronds/mo observed during the subsequent period). For these reasons, we decided to use data from the whole censused period to calculate total stem growth and frond production. Mean height growth rates for *C. divergens* were 8.0 ± 1.0 mm/mo in open canopy, and 13 ± 2.1 mm/mo in 50% shade. Mean

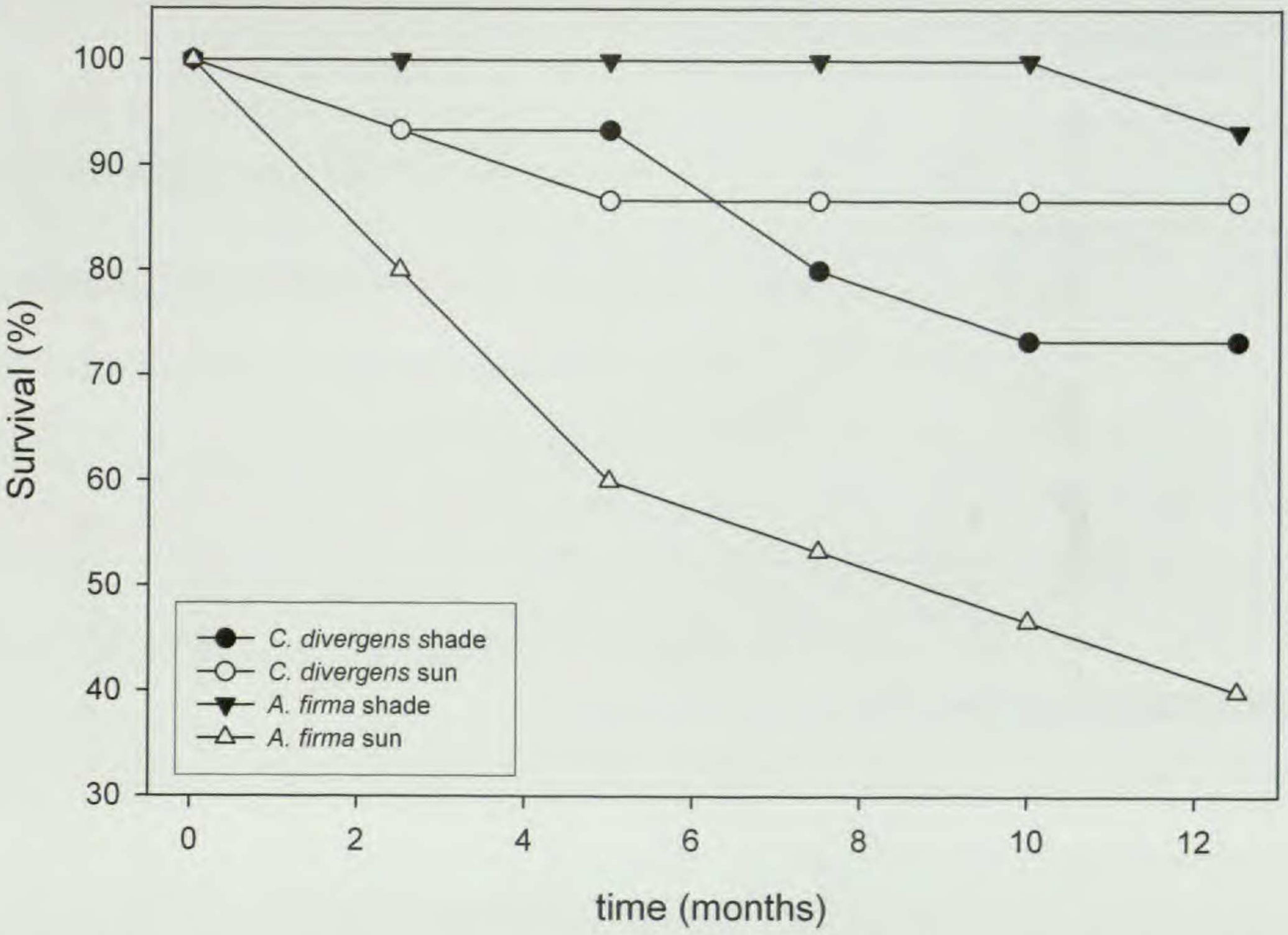

FIG. 3. Survival curves of transplanted *Cyathea divergens* and *Alsophila firma* individuals to a 50% shaded greenhouse and an open common garden near Cuetzalan del Progreso, Puebla.

height growth rates for *A. firma* were 2.0 ± 1.4 mm/mo in open canopy and 6.0 ± 0.8 mm/mo in 50% shade. Height growth rates were higher for *C. divergens* than for *A. firma* (Fig. 5(A); ANOVA, $F_{1,41} = 23.0$, $P < 0.001$), and were higher under shade than in sunny conditions (Fig. 5(A); ANOVA, $F_{1,41} = 9.0$, $P < 0.001$).

Frond production was not related to initial stem height (*C. divergens*: Pearson, $r < 0.65$, $P > 0.5$ in shade and $r < 0.5$, $P > 0.5$ in sunny conditions; *A. firma*: Pearson, $r < 0.6$, $P > 0.25$ in shade and $r = 0.295$, $P > 0.95$ in sunny conditions). Consequently, this variable was not considered as a covariate in the comparisons between species and treatments. Individuals of *C. divergens* produced 13.9 ± 0.85 and 15.5 ± 0.89 fronds/yr in open canopy and 50% shade, respectively, while *A. firma* individuals produced 6.8 ± 0.97 and 10.4 ± 0.53 fronds/yr in open canopy and 50% shade, respectively. *Cyathea divergens* produced more fronds per yr than *A. firma* (Fig. 5(B); ANOVA, $F_{1,35} = 47.5$, $P < 0.001$). Both species produced more fronds under 50% shade than in open canopy (Fig. 5(B); ANOVA, $F_{1,35} = 7.8$, $P < 0.001$).

DISCUSSION

Cyathea divergens was the most abundant tree fern species found along roadsides near Cuetzalan. This might result from a higher abundance of the

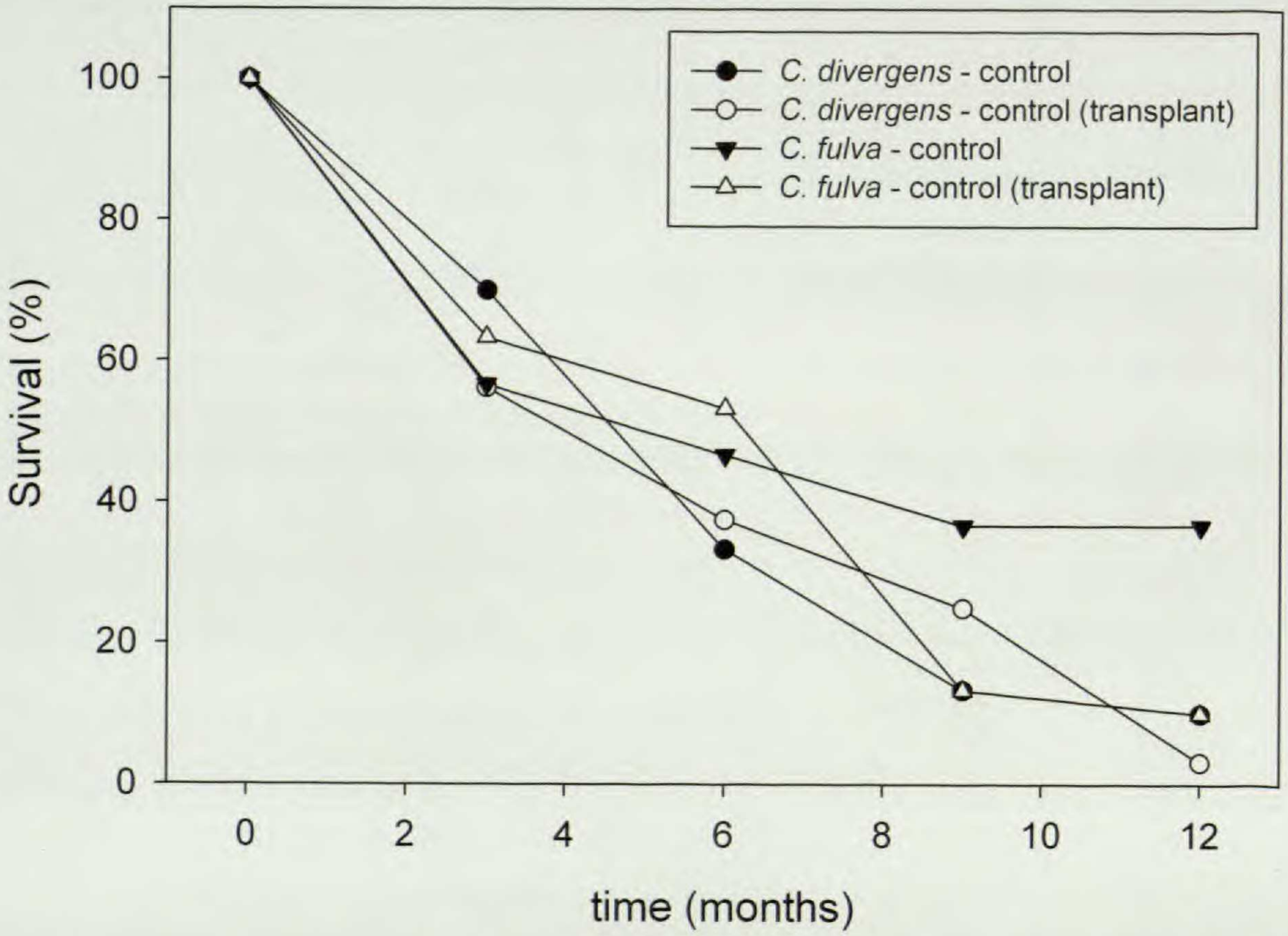

FIG. 4. Survival of transplanted *Cyathea* spp. under two experimental treatments in Cuetzalan del Progreso, Puebla. Treatments corresponded to: (1) control – individuals marked on roadsides; (2) transplanted control – individuals marked and transplanted to the roadsides areas from where they were extracted.

species in the region, together with an adaptation to environmental conditions in disturbed areas. In contrast, we encountered only young individuals (< 1.0 m in stem height) of *A. firma*, all located within an intermediate altitudinal range. Apparently, the conditions experienced in disturbed areas are not appropriate for the establishment and long term survival of this species. All studied species, except *C. divergens*, were unevenly distributed across altitudinal ranges. Air humidity and temperature, soil moisture content, and other environmental conditions that vary with elevation may restrict the habitat range of the less adaptable species. This distinct species' abundance and the variation in the number of tree ferns sampled in each altitudinal range have to be considered for selecting proper sites for extracting seedlings or transplanting them. In addition, species' abundances in natural populations and in a broader range of disturbed areas should be assessed in order to provide reliable management and conservation strategies for tree ferns in the area.

A higher number of transplants of *C. divergens* survived when planted in safe sites, whether they were located in sunny or shade conditions, compared to the controls left along roadsides (see Figs. 3 and 4). In such sites, tree ferns recurrently suffer damage due to weeding. Damage may have stressed young

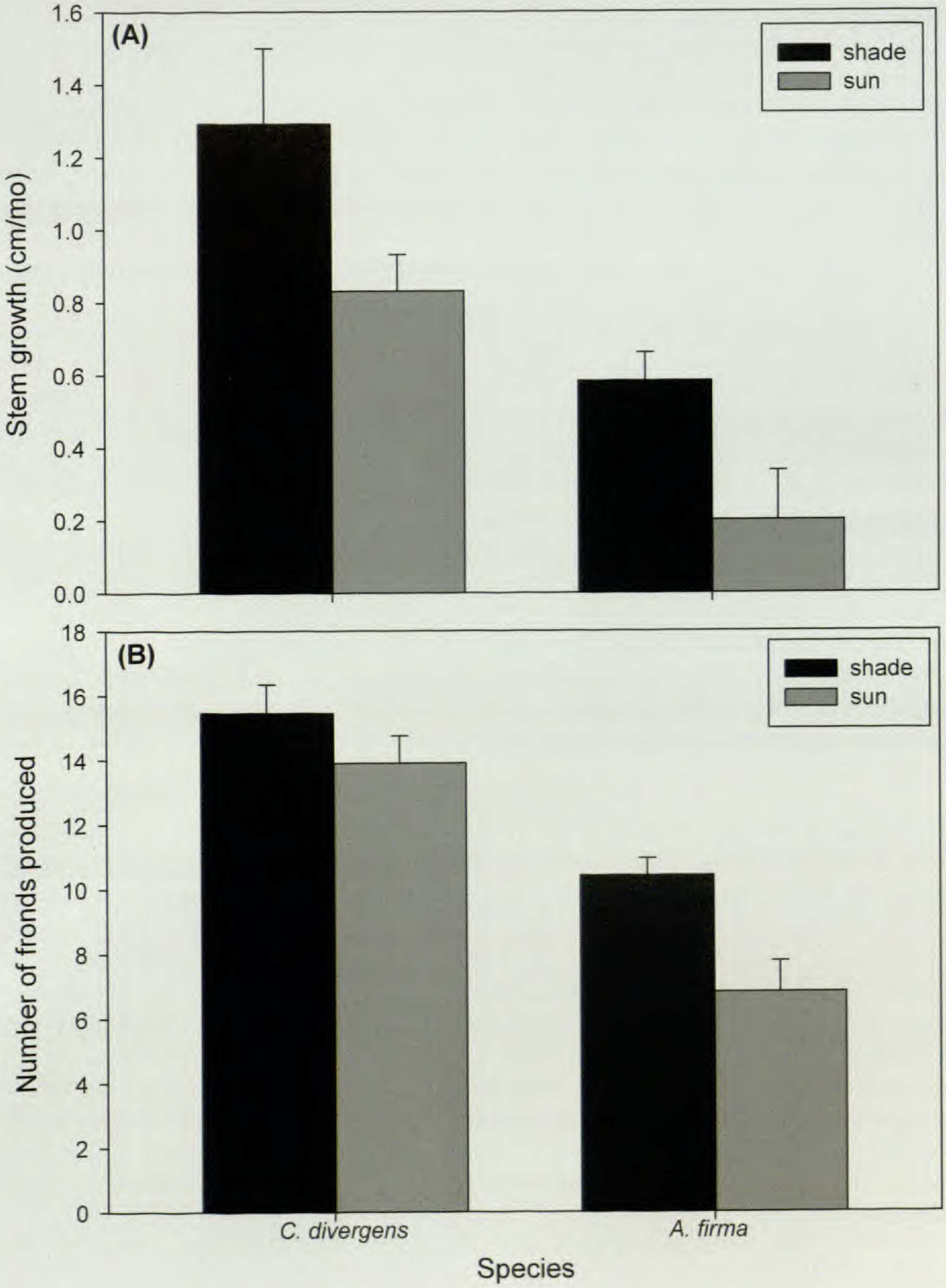

FIG. 5. (A) Height growth (± SE) for transplanted individuals of *Cyathea divergens* ($N = 11$ shaded, $N = 13$ in the open) and *Alsophila firma* ($N = 14$ shaded, $N = 6$ in the open) near Cuetzalan del Progreso, Puebla. (B) Production of new fronds (± SE) in transplanted individuals of *Cyathea divergens* ($N = 11$ shaded, $N = 10$ in the open) and *A. firma* ($N = 12$ shaded, $N = 5$ in the open) near Cuetzalan del Progreso, Puebla. All differences were statistically significant ($P < 0.05$).

tree ferns beyond their capability to recover, causing their death. Although not statistically significant, survival rates of *C. fulva* were higher in control than in control transplant treatments after 1 yr. Tree ferns of this species may not overcome the stress caused by transplantation. Further studies are necessary to assess the adequate conditions that would increase the survival of transplants of *C. fulva*. In general, survival rates were greater when tree ferns were transplanted to safe sites. However, because our experiments do not allow for comparisons among sites for species other than *C. divergens*, more solid information about the survival of transplants will depend on future experiments, in which each species is subjected to all treatments.

Survival rates were statistically similar for tree ferns relocated to safe sites under sunny or shade conditions. Bernabe *et al.* (1999) observed the same pattern for two of the three tree fern species they studied in tropical montane forests of Mexico. As suggested by these authors, tree fern species vary in their tolerance to different light conditions. In our study, both *C. divergens* and *A. firma* seemed to tolerate a wide range of light availability. However, the survival rate for *A. firma* planted in the shade was higher, although not statistically significant, than in the sun treatment. The ability to branch by adventitious buds may confer this species a higher tolerance to the stress caused by transplantation. For *A. firma*, shade conditions, in which water stress is diminished, may be ideal for transplantation, at least during establishment, until the transplants produce their first expanded leaves. Further differences in survival could have been observed if younger and, therefore, more vulnerable, transplants were used, and if we had a bigger sample size or our observations were prolonged for more than 1 yr.

Several studies on tree ferns have focused on understanding the plasticity of phenological responses of many species and the effects of such plasticity on population dynamics (e.g., Hunt *et al.*, 2002; Mehltreter and García-Franco, 2008). Adaptations to different light conditions have particularly been addressed for several species (Arens, 2001; Ash, 1987; Bernabe *et al.*, 1999; Seiler, 1981, 1984; Walker and Aplet, 1994). In sunny conditions, for example, several *Cyathea* species often grow faster in height, produce more fronds and start to reproduce earlier than in shady conditions (Arens, 2001; Ash, 1987; Bittner and Breckle, 1995; Poulsen and Nielsen, 1995). On the other hand, *Dicksonia antarctica* Labill seems to grow slower in sunny sites, when compared to less exposed and more humid sites, where they are less likely to experience water stress (Hunt *et al.*, 2002). Different light intensities can also cause changes in crown architecture of some *Cyathea* species (Arens and Sánchez-Baracaldo, 2000; Cox and Tomlinson, 1985; Tanner, 1983).

In our study, transplants of both *C. divergens* and *A. firma* placed in the shade grew faster in height and produced more fronds than those planted in sunny sites. Our data is in contrast to what has been observed for other tree fern species, which grow faster when exposed to conditions of higher light availability (see Arens, 2001; Arens and Sánchez-Baracaldo, 1998; Ash, 1987; Bittner and Breckle, 1995; Bernabe *et al.*, 1999; Seiler, 1981). These results may reflect a faster adaptation of transplants to shade conditions. When planted in

the shade, tree ferns would experience lower air temperature, higher air humidity and soil moisture availability. Under such conditions, water uptake would probably be adequate, and transpiration rates would not be elevated. Photosynthesis limitation by water availability would probably be lower when transplants are placed in the shade, in comparison to sunny sites, allowing tree ferns to grow faster and produce more fronds.

Transplantation is a low cost- and time-demanding activity that would adequately enhance both *in* and *ex situ* conservation of tree fern species in the region of Cuetzalan. Potentially, young tree ferns transplanted from sites in which they experience elevated mortality could be used as ornamental plants, promoting the *ex situ* conservation of native *Cyathea* spp. in the region. Our study suggests that transplants of *C. divergens* could be successfully used in gardening. Under adequate conditions, this species showed high survival and growth rates. More concrete conclusions should rely on complementary studies with a larger number of transplants by species, divided into replicate sites.

Additional support for the *ex situ* conservation of *C. divergens* comes from the fact that it is probably the most harvested species for handicraft production (Eleutério and Perez-Salicrup, 2006). Transplants could also be used for the conservation of rare species, such as *A. firma*, which is considered to be at risk of extinction (Diario Oficial de la Federación 2001).

Many local farmers, for example, have manifested interest in transplanting tree ferns to the understories of their shade coffee plantations. Given that our study shows that young tree ferns should be preferentially transplanted to sites where they are not exposed to direct sunlight, this use by local farmers may be successful. Moist and shaded conditions provided by the canopy of shade coffee plantations are probably adequate for a successful establishment and growth of transplants. Tree ferns could potentially survive and satisfactorily grow associated with this land use if they are protected from accidental damage during agricultural activities. If a few requirements are met, transplantation might also be the opportunity for local farmers to engage in the responsible management and trade of transplanted *Cyathea* spp. individuals.

The trade of more abundant and less endangered tree fern species would additionally require more than current market assessments and future market predictions. Detailed studies about the state of native tree fern populations occurring in forest remnants in the region are essential to provide policies that benefit *in situ* conservation and limit tree fern exploitation. In addition to limiting tree fern exploitation, the extraction of tree ferns from disturbed areas and native populations in forest remnants should be exclusive to local landowners, who depend on the exploitation of forest natural resources for their livelihoods (see Pérez-García and Rebollar-Dominguez, 2004).

Finally, our study emphasizes the importance of disturbed areas for the conservation of endangered species. These areas may constitute not only important sources of young tree ferns, but also seedlings of other species.

Therefore, the use of transplants for promoting conservation is worth testing for other species, sites, and environmental conditions.

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